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# A Surface Wave Transmission Line

*This article is the first in a series of QEX articles that involve surface wave transmission line theory and applications for use by radio amateurs. The second article describes a new theory for understanding antennas. The third article describes a very wide band antenna.*

Many we've shown this to have a first response of something like "How can a signal hooked to a long wire not radiate?" This particular type of transmission line has not been previously described in the Amateur Radio literature, but it may be mistaken for one that has. Surface wave propagation has been known for a very long time. In fact, in the early days of radio, prior to 1900, theoretical work was done by Sommerfeld to explain beyond the horizon propagation. Then in the 1950s, Georg Goubau introduced a new surface wave transmission line (SWTL) that required only a single conductor.[1] That line, known since as "G-line," required dielectric (insulation) around the wire or else special featuring of the conductor to slow the relative velocity of propagation in order to keep the signal from leaving the wire conductor. Reference books, including *The ARRL VHF Manual*, provided information from Goubau's work and a 1974 *QST* article by George Hatherell, K6LK, further described the use of this unusual mode for amateur radio purposes.[2, 3]

The SWTL being described here does not use the same mode as described for G-Line. Unlike G-line, no insulation or conditioning around the conductor is necessary. In fact, a bare conductor can actually work better than one with insulation, at least while the surface is bright and shiny. Also, there is no slowing of the propagating wave. The wave may travel more than 50% faster than signals in common coax and has been measured to have a relative propagation velocity of unity — it travels right at the speed of light.

For those who are familiar with antennas and have difficulty understanding that this SWTL isn't one, it is perhaps useful to first consider the familiar dipole. A dipole can make a good antenna, particularly when it is an odd number of half wavelengths long. You may have operated a 40 meter dipole on both 40 and on its 3rd harmonic at 15 meters. A dipole can be fed from the middle and exhibits resonance at the fundamental, 3rd, 5th and higher odd harmonics.[4] In a sense, a resonant dipole, "knows" how long it is — that is, by connecting only at the center, responses due to total length can be seen. A dipole's response depends upon the length and on something happening at the element ends.



**Completed 400 MHz launcher mounted on a "holder." The no. 24 SWTL conductor extends from the center of the horn and can be seen as a faint line in this photograph.**

A monopole fed against a ground can be thought of rather like a dipole. Fed from one end, the signal (wave) travels to the far end of an element and is reflected back from the discontinuity there. Since the conductor ceases at the end, real current is zero and voltage is highest there. As a result of that discontinuity a free wave is radiated into the surrounding space while at the same time a reflected wave returns toward the center.

A dipole simultaneously exhibits properties characteristic of a radiator, a transmission line and a resonator.[5] A monopole element fed from the end does this as well.

If we put a load at the far end of an element that is able to couple to the signal (wave) and prevent both reflection and radiation, then the resonance disappears and signal energy goes into that load. If you've ever grabbed the end of a driven element of a VHF or UHF Yagi with your hand while watching an SWR meter you have witnessed this effect. The structure operated less like an antenna. Depending upon whether you were transmitting or receiving, signal power to or from a distant location was reduced, resonance was suppressed and some of the transmitted energy was absorbed in your hand. Under these conditions, the driven element became more of a transmission line and less of a radiator. Energy put into the element traveled as a wave along the conductor and was absorbed into a load at the end. With appropriate coupling and loading, this behavior can occur at all frequencies, not just at frequencies where the unloaded element happens to be resonant. With proper connections, called "launchers" at each end of a conductor, a simple transmission line that exhibits very low attenuation along with very wide bandwidth operation can result. The plot in Figure 1 compares the measured attenuation of 100 feet of a SWTL made from no. 24 AWG copper wire conductor with the attenuation of LMR400 coax. Not only is this SWTL simpler, less expensive

[1]Notes appear on page 9.

**Table 1 Materials and Sources for Building the Launcher**

1. Pacon® Metallic-Colored Four-Ply Poster Board: **www.amazon.com/Pacon%C2%AE-Metallic-Colored-Four-Ply-Poster-Carton/dp B002XJHGDK/f=sr_1_3?ie=UTF8&s=office-cts&qid=1309381399&sr=8-3**
2. SMA connector: **www.jameco.com/webapp/wcs/stores/servlet/Product_10001_10001_159531_-1**
3. 0.005 inch brass shim stock: **www.amazon.com/Brass-Shim-Stock-0-005-Thick/dp/B00065UXZG**
4. No. 24 Magnet wire: **www.frys.com/product/6279330**
5. Metal tape: **www.amazon.com/Shurtech-Brands-50-47523-01-Metal-Repair/dp/B0050BY230**
6. K&S brass tubing stock in various sizes: Available from many local hobby and hardware stores.
7. Styrofoam insulation, 2 inches thick: Available at most home building supply stores.

and lighter than coax, but above a lower frequency limit which is determined by the launcher design, it can also exhibit lower loss than even this excellent coax.

While the preceding discussion may help describe the SWTL for those familiar with antennas, the question "How can a transmission line as simple as this not have been discovered and used before?" may still occur. For those who prefer to examine the SWTL from the point of view of transmission line rather than antenna theory, more detail on the theory, historical background and operation of this SWTL is available.[6] In the rest of this article we'll just show you how to make and use it.

## Fabrication

The launchers use broad band coaxial transmission line transformers described by Klopfenstein and having a Chebyshev impedance taper that matches a 50 Ω coaxial connection at the narrow end to the 377 Ω impedance at the wide end, where the SWTL conductor attaches.[7] This transformation has a low frequency limit set by the lowest frequency at which the total transformer length is approximately one half wavelength. Two designs are shown here, one with a 400 MHz lower limit and the other with a 144 MHz lower limit. Both designs should operate from their low frequency cut-off to well above 3 GHz. The outer conductor of these coaxial transformers is a cone made from metalized paper. The inner conductors, which have specially varying diameters to provide the correct impedance profile along the length of the launcher, are made from brass tubing. Table 1 lists the materials needed to build the launchers, with one source.

### 400 MHz Launcher Fabrication

Cut the metalized paper and the brass shim stock from flat stock using the patterns shown in Figure 2A. Using a cloth and some acetone, clear the gold ink away from the paper in the indicated area prior to folding it into a cone with the metalization on the outside. With the overlapping tab lined up along the entire inside length, temporarily tape the cone together on the inside with transparent tape or masking tape. Then go back and tape the entire outer seam with metal foil tape. It may help to have two people for this operation.

Similarly, with the brass shim pattern, once cut out, overlap the edges carefully and tack solder it in a few places to hold it in place before going back and completely soldering the seam.

When you are finished building these cones, the brass cone should fit snugly over the narrow end of the metalized paper cone and the brass and cleared metalization should have good electrical contact.

The center conductor is fabricated from K&S Metals brass tubing stock, as shown in Figure 2B. This brass tubing is available in 1⁄32 inch diameter steps from many hobby and hardware stores. Figure 2B shows at what position along the tapered center the next size begins. Cut the tubing about ½ inch longer than the required length to allow for overlap at each end. Carefully position these, both as to length and straightness, and tack solder them together. Once you have the entire tapered center conductor assembled and are pleased with the lengths and alignment, you can go back and solder each joint completely. Finally, sand or file away any excess solder so that you finish with a smooth step-tapered center conductor.

Cut a Styrofoam stiffener from 2 inch stock. This is available from home supply stores for use as thermal insulation. If possible, cut the circle using a small band saw with the table tilted to provide about a 22° angle, so that it will fit snugly in the finished paper cone about ⅔ of the way toward the open end. Drill an ⅛ inch hole through the center of the stiffener.

For final assembly, shown in Figure 3, first slip the brass cone over the center conductor and then solder the SMA connector center pin into the end of the tube. Set the paper cone on a flat work surface, wide end down, and seat the brass cone over the

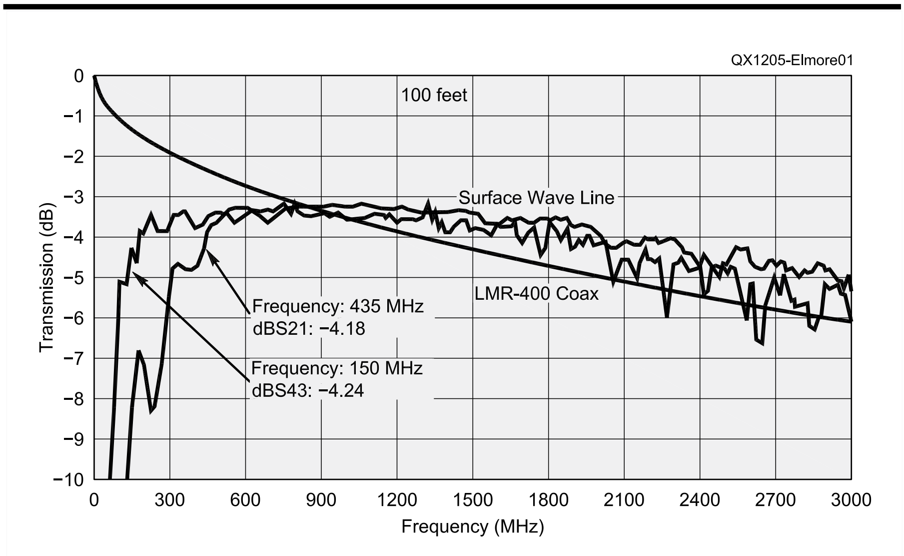
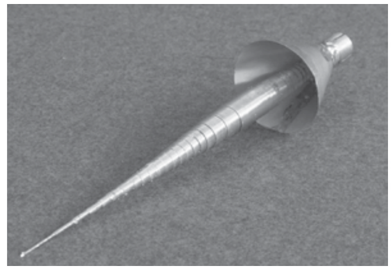
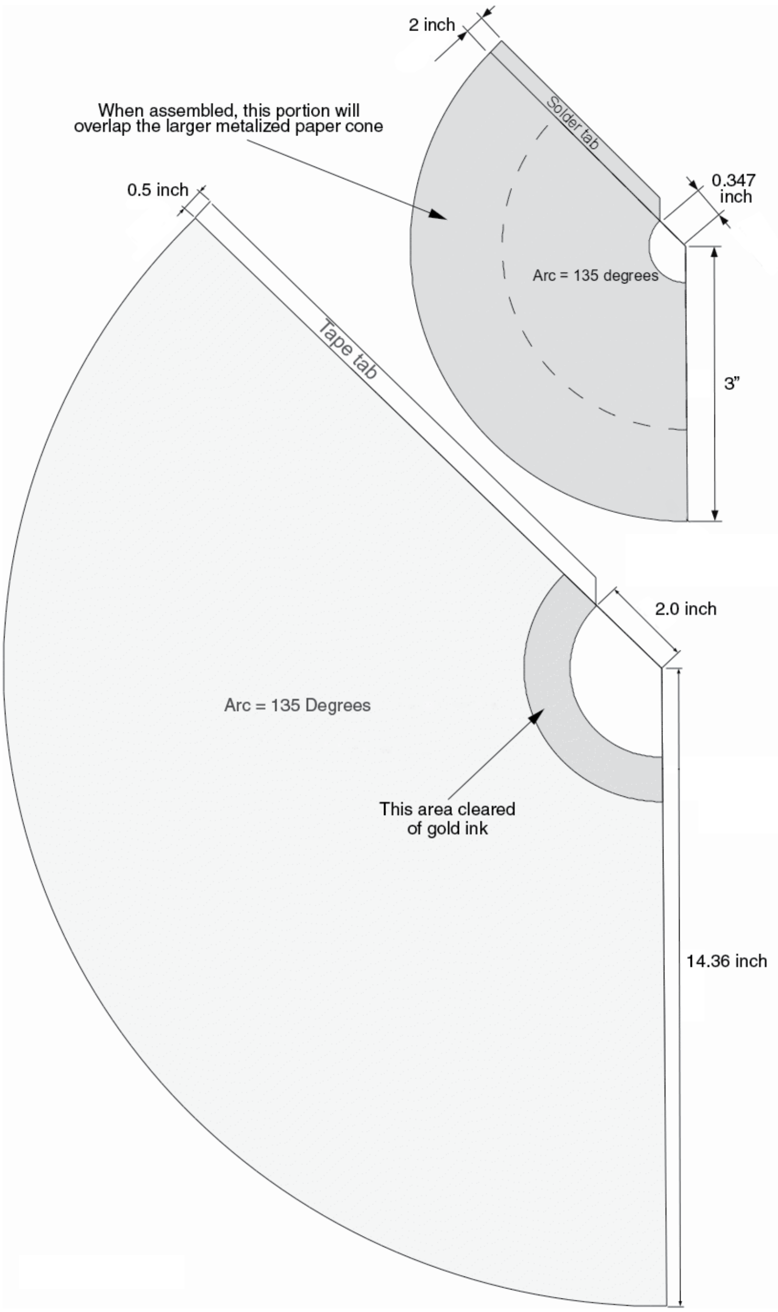



**Figure 1 — Measured performance of SWTL compared with measurement of Times Microwave LMR-400 coaxial cable. Plots of 100 feet of no. 24 AWG conductor with a pair of 400 MHz launchers and a pair of 144 MHz launchers are shown. The main difference between these is the cut-off frequency.**








| K&S Tubing Diameter 32nd of an Inch | Distance From SMA Connector |
|---|---|
| 3 | Flush with Teflon on SMA |
| 4 | 0.06 |
| 5 | 0.17 |
| 6 | 0.28 |
| 7 | 0.4 |
| 8 | 0.51 |
| 9 | 0.64 |
| 10 | 0.76 |
| 11 | 0.89 |
| 12 | 1.03 |
| 13 | 1.16 |
| 14 | 1.31 |
| 15 | 1.46 |
| 16 | 1.62 |
| 17 | 1.79 |
| 18 | 1.98 |
| 19 | 2.19 |
| 20 | 2.43 |
| 21 | 2.72 |
| 22 | 3.14 |
| 21 | 4.38 |
| 20 | 4.83 |
| 19 | 5.17 |
| 18 | 5.45 |
| 17 | 5.71 |
| 16 | 5.95 |
| 15 | 6.18 |
| 14 | 6.41 |
| 13 | 6.61 |
| 12 | 6.84 |
| 11 | 7.07 |
| 10 | 7.3 |
| 9 | 7.55 |
| 8 | 7.8 |
| 7 | 8.07 |
| 6 | 8.37 |
| 5 | 8.71 |
| 4 | 9.09 |
| 3 | 9.56 |
| 2 1 | 0.17 |
| 1(Wire) | 11.11 |
| front 12.99 | |

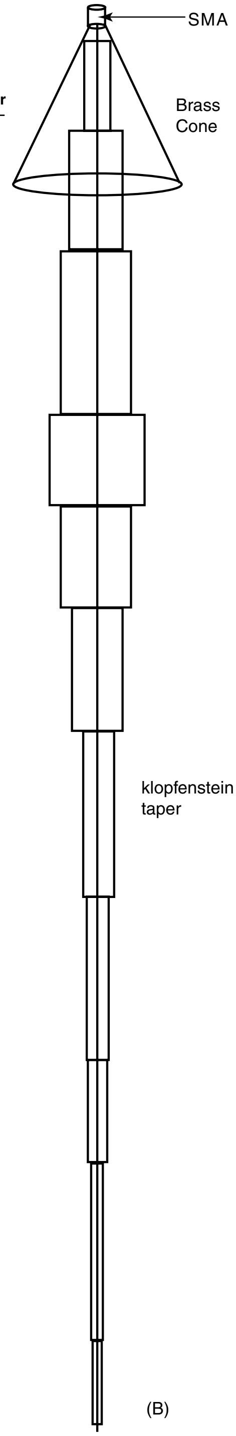



**Figure 2 — Part A shows the metalized paper and brass shim stock cone patterns before folding. Part B gives the dimensions of the inner launcher tapered conductor sections made from K&S Metals brass tubing (in 32nds of an inch) versus position from the SMA connector for the 400 MHz launcher.**

paper cone while guiding the tapered center conductor through the Styrofoam stiffener. The center hole will enlarge slightly as the center conductor pushes into it. With everything in alignment, you can then solder the SMA connector flange to the brass cone. Use metal tape to fasten the brass cone to the paper cone and your 400 MHz Klopfenstein taper launcher is complete. You only need to solder the no. 24 copper line to the center conductor at the wide end of the tube to use the launcher.

### 144 MHz Launcher

The 144 MHz version of the launcher is simply a "stretch" version of the 400 MHz version. Both should operate to well beyond 3 GHz, but the 144 MHz version, at a little over 40 inches of overall length, will operate at lower frequencies as well — including the 2 meter and 1¼ meter amateur bands.

Construction is basically the same as already described for the 400 MHz version except that significantly more brass tubing is required for the center conductor, and three sheets of metalized paper are needed to construct the outer cone.

Figure 4 provides a template for the paper cone and Figure 5 is a template for the brass cone. The inner conductor dimensions are listed in Table 2. An SMA connector is used the same way as it was for the 400 MHz launcher.

The target impedance profile for a 20 dB return loss Klopfenstein taper wide band transmission line transformer is shown in Figure 6. This same profile can be scaled in length for different lower frequency limits. When built from stepped diameter tubing sections rather than continuously varying line diameters, the performance is just slightly poorer than this target.

Figure 7 shows the measured transmission attenuation and impedance match of the line, both as return loss and SWR. As shown, it has a corner frequency just below 2 meters but the line is actually usable from below 100 MHz and has a usable upper limit well above 3 GHz. Actual performance is probably somewhat better than shown by the measurement because the calibration of the vector network analyzer used to measure it was compromised due to variations in the 100 foot long test cables and connections that were required for measuring this large structure. After calibration with precision standards, the lines had to be dragged to the ends of the SWTL and were flexed in the process. This reduced the resulting measurement accuracy.

**Table 2**
**Step-tapered Center Conductor Dimensions for the 144 MHz Launcher**

| *K&S Tubing OD, (32nds of an inch)* | *Position from SMA (inches)* |
|---|---|
| 3 | 0 |
| 4 | 0.18 |
| 5 | 0.51 |
| 6 | 0.85 |
| 7 | 1.20 |
| 8 | 1.56 |
| 9 | 1.93 |
| 10 | 2.30 |
| 11 | 2.70 |
| 12 | 3.11 |
| 13 | 3.52 |
| 14 | 3.96 |
| 15 | 4.43 |
| 16 | 4.92 |
| 17 | 5.43 |
| 18 | 6.00 |
| 19 | 6.63 |
| 20 | 7.36 |
| 21 | 8.25 |
| 22 | 9.53 |
| 21 | 13.27 |
| 20 | 14.65 |
| 19 | 15.67 |
| 18 | 16.52 |
| 17 | 17.30 |
| 16 | 18.03 |
| 15 | 18.74 |
| 14 | 19.43 |
| 13 | 20.04 |
| 12 | 20.73 |
| 11 | 21.42 |
| 10 | 22.13 |
| 9 | 22.87 |
| 8 | 23.64 |
| 7 | 24.47 |
| 6 | 25.37 |
| 5 | 26.40 |
| 4 | 27.56 |
| 3 | 28.96 |
| 2 | 30.81 |
| 1 | 33.66 |

Note: The last tubing section is 1⁄32nd inch OD and extends to the front of the paper cone, where it is soldered to the no. 24 wire SWTL conductor.

## SWTL Line Use

For simple transmission line use, you'll need to make two of the above launchers, of either the 400 MHz or the 144 MHz versions. Once these are built, to use the line, simply reel out the desired length of no. 24 bare copper or enameled magnet wire, tin the ends and solder it into the center conductors of each launcher. Some sag in the line is really not a problem but it is important that the line be kept away from the ground and obstacles, preferably by at least a foot or more, over its entire length. If you use it this way, you should have a low attenuation, very broadband transmission line that can be used just like any other line for connecting a receiver or transmitter to an antenna or any similar transmission line use over the 400 MHz to 3 GHz or 144 MHz to 3 GHz range, as shown by Figure 1.

As you can see in Figures 2B and 3, we soldered a ½ inch copper water pipe coupling on the back of the brass cone and around the SMA connector to facilitate mounting each launcher. Prior to soldering, we slotted the open end of this fitting so that the entire launcher could be supported from a piece of standard ½ inch copper pipe and an SMA fitted coaxial cable could be run down the center of that same mounting pipe and secured with a small metal hose clamp.

Very long runs of this line may be quite useful in connecting a transceiver to a distant antenna, perhaps one located at the top of a tower or a nearby hill. If very long lines are used, the weight of the line may be partially borne by intervening Styrofoam supports, periodically placed along the span, to keep the wire away from ground and obstacles. The use of insulators that have higher relative

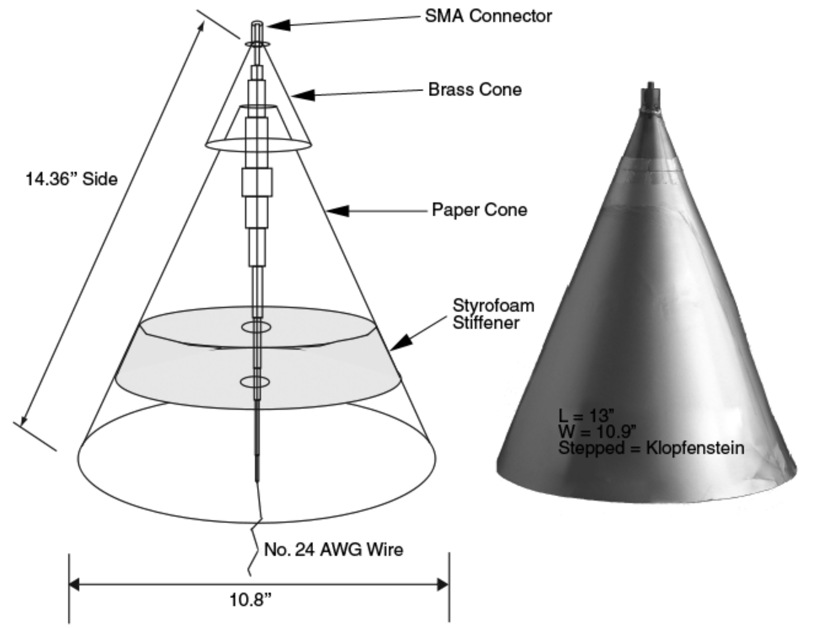
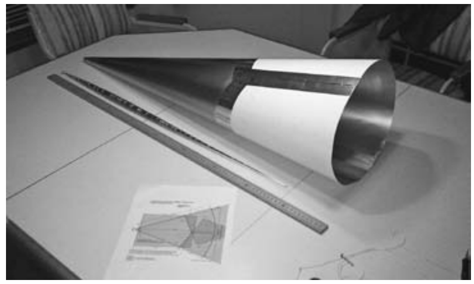



Figure 3 — Assembly of the 400 MHz Launcher.



This photo shows a 144 MHz cone, along with the Klopfenstein taper impedance matching line and the template sheet for the cone.



Here is a completed 144 MHz launcher, mounted to a wooden frame for testing.

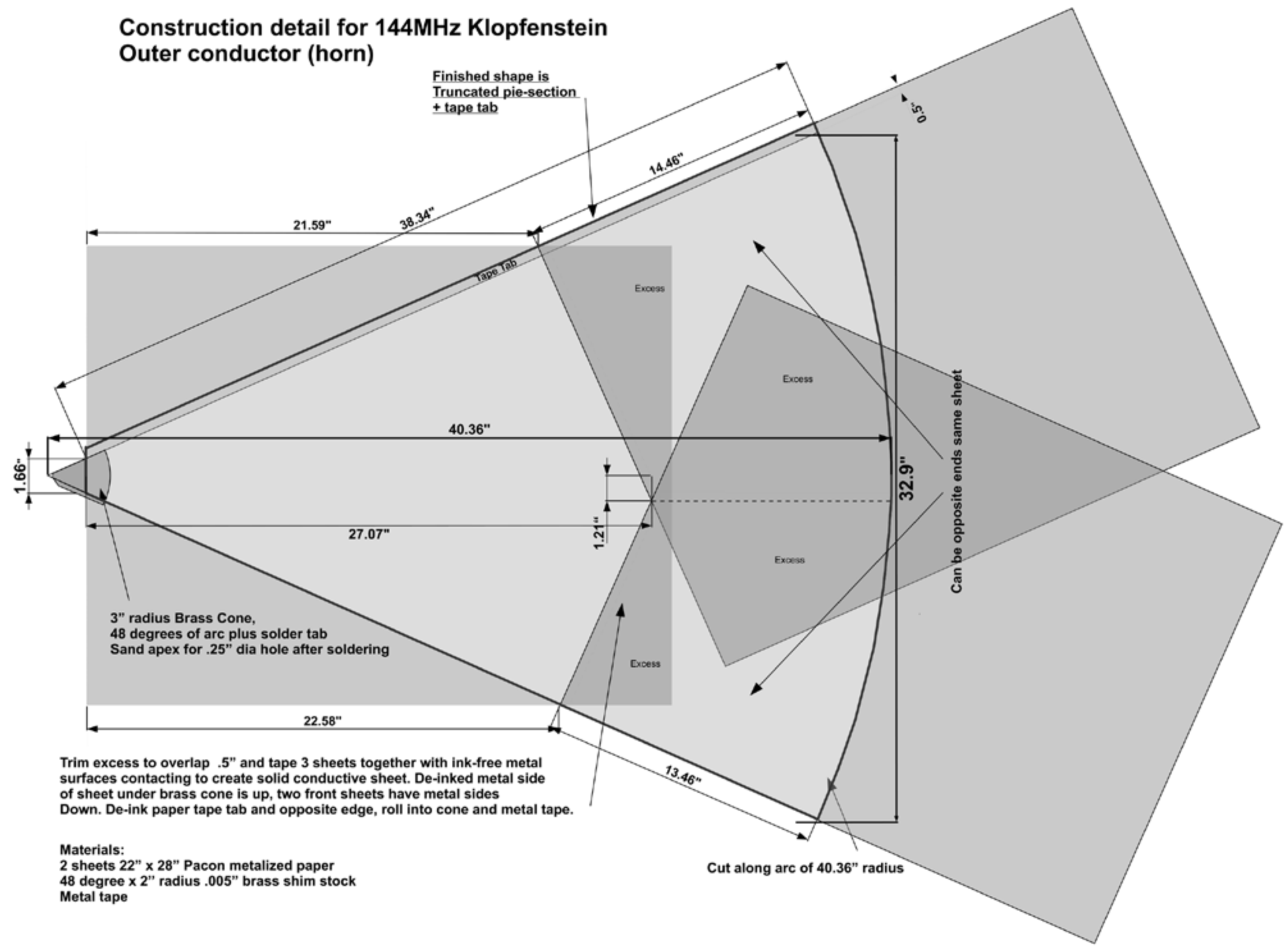



Figure 4 — The paper cone for the 144 MHz version of the launcher requires three 18 × 24 inch sheets of metalized paper.

dielectric constants such as ceramic or glass, however, will tend to unbalance the wave on the line and will cause additional attenuation and reflection so should be avoided.

If you accidentally break the no. 24 conductor, even if you are using enamel covered magnet wire, it isn't necessary to re-solder in order to reattach. A linesman's splice made by twisting one to two inches of each end tightly and closely around the other end will provide a "gimmick" capacitor that will make quite a good connection at 400 MHz and above. Because the characteristic impedance of the line is 377 Ω, it doesn't take much capacitance to make a very adequate RF connection even if there is insulation that prevents a dc connection. At lower frequencies you should make the splice longer or else solder any break, keeping the overall length and diameter of the splice as small as is practical.

It is possible to substitute different wire diameters. Particularly for very long lines that are supported at intermediate points with Styrofoam, you may find you can achieve lower losses by going to significantly larger and heavier wire or conductor diameters. Particularly if you taper gently between different diameters, perhaps by using intermediate diameters for a few inches at the transition, you should be able to achieve very low loss on extremely long runs. Because line attenuation is primarily influenced by the conductivity of the SWTL conductor used and further limited by skin effect, large diameter conductors made from copper will tend to show better performance than small ones made from metals having poorer conductivity. Even so, because of the high characteristic impedance of the line, materials that might not normally be considered for RF use, such as iron or stainless steel, may be used to create a very adequate SWTL. Commercial applications of this SWTL have used ¼ to 2 inch diameter aluminum power line cables to achieve good performance even at 5 GHz and above. It is common to see attenuation at microwave of around 2 dB/100 feet with these larger conductors. For Amateur Radio applications, it may prove convenient to use a tower or mast guy cable as a feed line as well as a mechanical support. If this is to be done, a different launcher design that doesn't put mechanical strain directly onto the launcher's coaxial cable center pin must be arranged. A launcher that mechanically and electrically clamps to the cable with an RF attachment one quarter wavelength in front of the attachment point is one possibility but is not detailed in this article.

It is also possible to use non-circular cross-section conductors, as long as they are radially symmetric. There has been a report of the use of metalized Mylar ribbon of very great lengths (a kilometer or more)

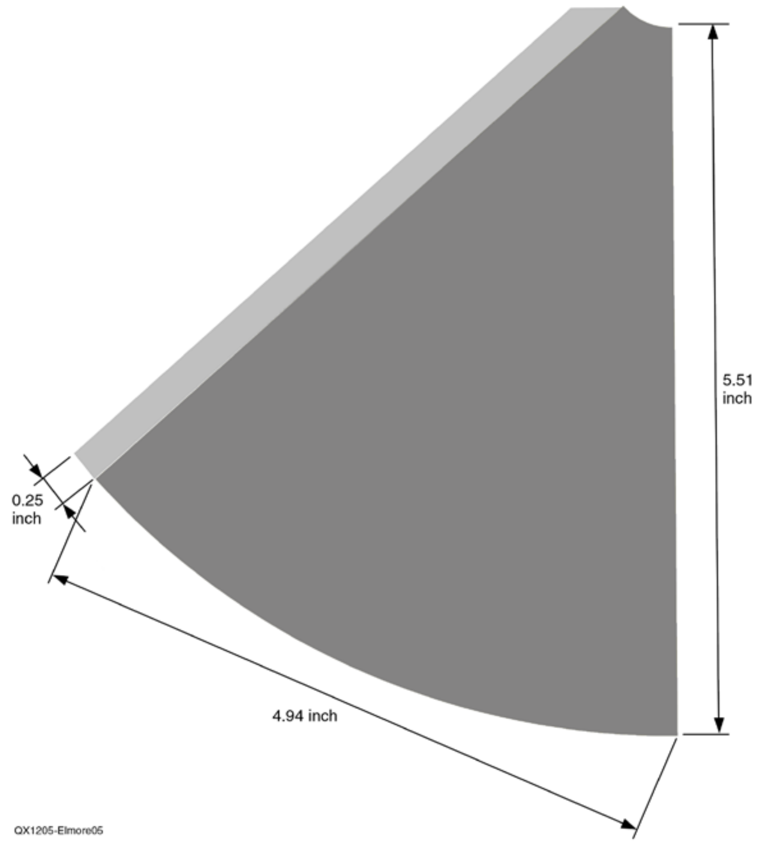



**Figure 5 — This is the template for the brass portion of a 144 MHz launcher outer cone. The material can be 0.01 inch thick brass shim stock.**

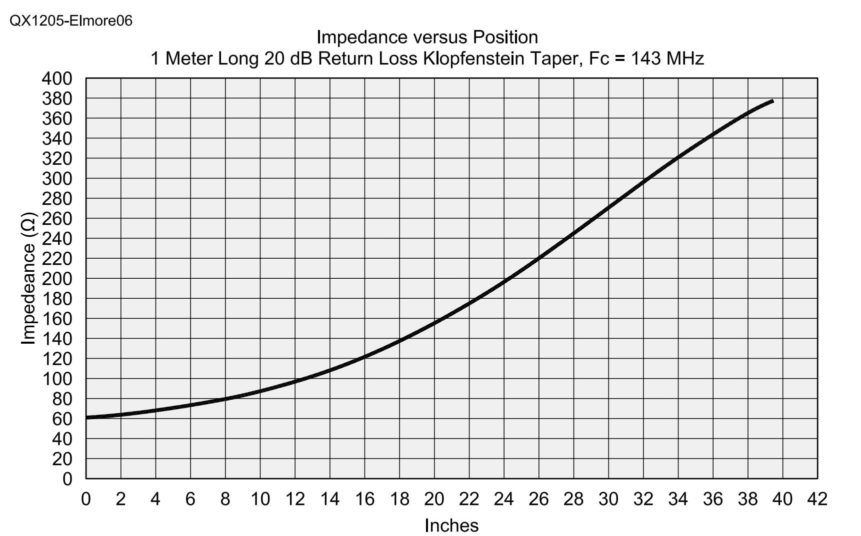



**Figure 6 — This graph shows the line Impedance versus position for a 20 dB return loss Klopfenstein taper with a corner frequency of 143 MHz.**



In this photo, a pair of 144 MHz Launchers are being measured with 100 feet of no. 24 magnet wire conductor in the driveway at N6GN. The vector network analyzer used for the measurement can be seen to the right, between the two ends.

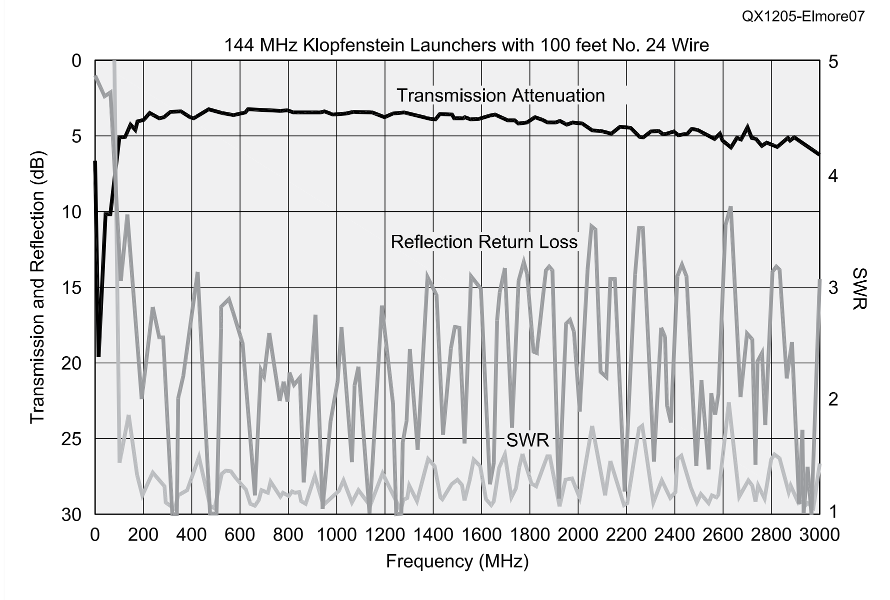



**Figure 7 — Here is the measured performance of 100 feet of SWTL line with 144 MHz Launchers.**

as a SWTL transmission line conductor.[8] While this report implied that this was a form of Goubau line, it seems likely that it was actually operating in the same manner as the SWTL lines described here, in a TM00 mode, longitudinal e-field wave guide rather than as the transmission line described by Goubau.

This SWTL should have quite high power handling capacity, particularly with larger diameter conductors. The authors have not tried kilowatt level transmitting, but it is very likely that the SMA connector will be the limiting factor rather than the line itself

## Permission to Use

The surface wave transmission line technology described here is patented and requires licensing agreements to build or use. Corridor Systems Inc, the patent holder, is, however, permitting licensed Amateur Radio operators worldwide to build and deploy devices and systems which use it for their personal, non-commercial use, under the terms of their Amateur licenses. Any other use requires licensing from Corridor Systems Inc, 3800 Rolling Oaks Road, Santa Rosa, California 95404, USA.[9]


*Glenn Elmore, N6GN, has been a licensed Radio Amateur for the past 50 years, and has held call signs of WV6STS, WA6STS and now N6GN. He has held an Amateur Extra class license since 1972. For most of his working career, Glenn has been an electrical engineer involved with the design of RF and microwave test and measurement equipment, notably scalar, vector network and spectrum analyzers.*

*Glenn's Amateur Radio interests have included weak signal VHF/microwave operation including meteor scatter, EME, terrestrial DX as well as higher speed Amateur TCP/IP radios and networks. He has recently been active on WSPR, the weak signal reporting network. Glenn is an ARRL Member.*

*John Watrous, K6PZB, is an ARRL Member who was first licensed in 1956. Several times he has won the San Francisco VHF Contest in the QRP category. He is active in WSPR and has been working with Glenn Elmore on radio projects for over 20 years. For 34 years he taught people to behave more creatively in an Art Department at Santa Rosa Junior College, where he first used computers in art in 1983. He initiated the college's first on-line class in 1995. Retiring in 1997, John has focused his energy toward brainstorming ideas with Glenn, and building models in his shop. John holds a Masters Degree in sculpture and has always been interested in art and technology.*


## Notes


[1]C. E. Sharp and G. Goubau, "A UHF Surface Wave Transmission Line," *Proceedings of the IRE*, Vol 41, pp 107-109, January, 1953.

[2]*The Radio Amateurs VHF Manual*, Eleventh edition, ARRL, 1968, p 175.

[3]George Hatherall, K6LK, "Putting the G-Line to Work," *QST*, June 1974, pp 11-15, 152, 154.

[4]R. Dean Straw, N6BV, Ed, *Antenna Book*, 21st edition, ARRL, p 2-3.

[5]John Kraus, W8JK, *Antennas*, McGraw-Hill Book Company, 1950, p 2.

[6]Glenn Elmore, N6GN, "Introduction to the Propagating Wave on a Single Conductor," **www.corridorsystems.com/FullArticle.pdf**.

[7]R W Klopfenstein, "A Transmission Line Taper of Improved Design," *Proceedings of the IRE*, Jan 1956 p 31.

[8]M. Friedman and Richard Fernsler, "Low-Loss RF Transport Over Long Distances," *IEEE Transaction on Microwave Theory and Techniques*, Vol 49, No. 2, Feb 2001.

[9]For further information about the surface wave transmission line and Corridor Systems atent, see their website: **www.corridorsystems.com**